The use of neutrino beams from muon storage rings [1]

Alexey A. Petrov

Department of Physics and Astronomy
Johns Hopkins University
Baltimore, MD 21218

Abstract. I give a brief overview of the physics potential of short baseline experiments at neutrino factories, i.e. facilities providing high energy and high intensity neutrino beams, like the one planned to be built in connection with the proposed high energy muon storage ring. These facilities would offer a unique opportunity to perform new precision studies of QCD and electroweak interactions. New types of measurements, such as studies of gluon density of the nucleon via charmonium production and extractions of V_{cb} and V_{ub} CKM matrix elements, will become possible. Interesting new physics scenarios can also be explored.

I   MOTIVATION

The purpose of this talk is to overview physics goals for the short baseline experiments utilizing high energy and high intensity neutrino beams. These include standard model electroweak physics, novel tests of QCD, and rare processes sensitive to physics beyond the standard model (SM).

The standard model electroweak parameters that are conventionally measured in neutrino experiments are $\sin^2 \theta_W$ and the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix elements V_{cd} and V_{cs}. Given the intense high energy beam of neutrinos these measurements will certainly yield new precise values for these quantities. In addition, completely new measurements, like precision studies of V_{ub} and V_{cb} CKM matrix elements, will be possible. On the QCD side, neutrino-nucleon interactions are potentially the best probes of various valence parton distribution functions, both unpolarized and polarized, as well as the strong coupling constant α_s. One can also study various non-perturbative parameters, such as fragmentation

---

[1] Invited plenary talks given at 23rd Johns Hopkins Workshop on Current Problems in Particle Theory: Neutrinos in the Next Millennium, Baltimore, MD, 10-12 June 1999, and The International Conference on Physics Potential and Development of $\mu^+\mu^-$ Colliders, San Francisco, CA, 15-17 December 1999.

functions. Finally, there are interesting new physics scenarios that can be tested in neutrino interactions. These include supersymmetric extensions of the standard model with broken $\mathcal{R}$ parity (or any models with leptoquarks), new heavy neutral leptons or gauge bosons, etc.

A proposed muon storage ring should provide a highly collimated, high-intensity ν beam from muons decaying in the accelerator tunnel. The neutrino spectra can be easily calculated [1]; for instance, the ν_μ energy spectrum is given by $dN_{\nu_\mu}/dx \simeq 6x^2 - 4x^3$ with $x = 2E'_\nu/m_\mu$ being the normalized neutrino energy in the μ rest frame. E'_ν is easily related to the neutrino energy in the lab frame, $E_\nu = xE_\mu(1 + \cos\theta)/2$, where θ is a neutrino angle in the muon rest frame. Another advantage of this facility is that for sufficiently high muon energies the neutrinos are produced in thin pencil-like beams with an opening half-angle $\theta_\nu \simeq m_\mu/E_\mu$.

II   QCD AND ELECTROWEAK STUDIES

A   Measurements of $\sin^2\theta_W$

One of the most important parameters of the standard model is the weak mixing angle θ_W which represents the angle of rotation from the "gauge" basis to the "physical" basis where the mass matrix of the gauge Z boson and the photon is diagonal. One of the many possible definitions is the on-shell definition of $\sin^2\theta_W$

$$\sin^2\theta_W^{os} \equiv 1 - \frac{M_W^2}{M_Z^2}, \tag{1}$$

In neutrino-nucleon interactions $\sin^2\theta_W$ can be extracted using the Llewellyn Smith [2] or Pascos-Wolfenstein relations [3]. These methods involve measuring three total cross sections and forming three ratios,

$$R_\nu = \frac{\sigma(\nu N \to \nu X)}{\sigma(\nu N \to \mu^- X)}, \ R_{\bar\nu} = \frac{\sigma(\bar\nu N \to \bar\nu X)}{\sigma(\bar\nu N \to \mu^+ X)}, \ r = \frac{\sigma(\nu N \to \mu^+ X)}{\sigma(\nu N \to \mu^- X)}. \tag{2}$$

In the approach of Llewellyn Smith, these can be combined to obtain $\sin^2\theta_W$:

$$R_\nu = \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}(1 + r)\sin^4\theta_W + C_\nu$$

$$R_{\bar\nu} = \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}(1 + r^{-1})\sin^4\theta_W + C_{\bar\nu}, \tag{3}$$

where C_ν and $C_{\bar\nu}$ represent known QCD and electroweak corrections. Alternatively, a Pascos-Wolfenstein construction can be used to extract $\sin^2\theta_W$:

$$R^\pm = \frac{R_\nu \pm rR_{\bar\nu}}{1 \pm r}, \ R^- = \frac{1}{2} - \sin^2\theta_W + \frac{C_\nu - rC_{\bar\nu}}{1 \pm r}$$

$$R^+ = \frac{1}{2} - \sin^2\theta_W + \frac{10}{9}\sin^2\theta_W + \frac{C_\nu + rC_{\bar\nu}}{1 \pm r}. \tag{4}$$

This method is actually "cleaner" as the QCD and electroweak corrections partially cancel out in Eq. (4). These relations are now used to extract $\sin^2 \theta_W$ by CCFR/NuTeV collaboration and will be used again at νFMSR.

In addition to the methods described above, intense neutrino beams from the muon storage ring (νFMSR) should allow for another measurement of $\sin^2 \theta_W$, which involves neutrino-electron scattering. This method is theoretically "cleaner", as it involves scattering of two leptons. This measurement involve investigation of four neutrino-electron elastic cross sections $\nu_i(\bar{\nu}_i)e^- \to \nu_i(\bar{\nu}_i)e^-$ for $i = e, \mu$. The involved cross section are much smaller then the corresponding DIS cross sections described above, but theoretical clearness of this process and much improved neutrino beam intensity makes this measurement a realistic possibility. Of course, future determinations of $\sin^2 \theta_W$ from νFMSR should be comparable or better than the projected result of the SLAC E158 Moller scattering experiment, i.e. should measure $\sin \theta_W$ with relative accuracy of better then $a~few~\times 10^{-4}$. Preliminary studies [1] show that it is quite realistic.

B   CKM and quark densities

Extraction of the matrix elements of the Cabibbo-Kobayashi-Maskawa quark mixing matrix is one of the outstanding challenges in phenomenology of the standard model. It is most likely that Nature has chosen only three generations of quarks, so

$$
V_{CKM} = S_L^{u\dagger} S_L^d = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \tag{5}
$$

Currently, the *charm* quark sector of CKM is best studied in νN charged current interactions, where neutrino interacts with valence and sea quarks of the nucleon. For example, the CCFR collaboration has provided a direct measurement of $|V_{cd}| = 0.232^{+0.017}_{-0.019}$. Independent knowledge of the strange sea quark density should also provide an independent measurement of $|V_{cs}|$ as well. In the framework of a "naive" parton model,

$$
\begin{aligned}
\frac{d^2\sigma(\nu N \to \mu^+\mu^- X)}{d\xi dy} &= \frac{G_F^2 M E_\nu}{\pi} \{[\xi u(\xi) + \xi d(\xi)] |V_{cd}|^2 \\
&+ 2\xi s(\xi) |V_{cs}|^2\} \left[1 - \frac{m_c^2}{2 M E_\nu \xi}\right] D(z) B_c,
\end{aligned} \tag{6}
$$

where $\xi = x(1 + m_c^2/Q^2)$ in a "slow rescaling" model of Georgi and Politzer [4] and $D(z)$ is a charm fragmentation function. Thus, measuring $d^2\sigma$ at different values of ξ provides an independent measurement of $|V_{cd}|$ and $|V_{cs}|$, if quark densities are known well enough [5]. Otherwise, a multiparameter fit can be performed to determine both $q(x)$ and CKM matrix elements.

Even though in the above discussion a parton model was used, a problem of semiinclusive single particle production can be addressed model-independently using the formalism of perturbative QCD factorization theorems. In this framework, the essential problem of having a heavy quark in the final state is the fact that its mass brings an additional scale to the problem at hand. The presence of this scale might affect theoretical predictions by inducing large logarithms involving m_Q, which have to be resummed in order for perturbative expansion to make sense. A practical recipe for such resummation is provided by the prescription of Aivazis *et. al.* (ACOT) [6].

A future measurement utilizing high intensity neutrino beams would provide accurate determinations of various $q(x)$. It is interesting to note that future neutrino factories would be able to study production of the b-flavored mesons, which would allow for an accurate determination of the intrinsic charm content of the nucleon. If an x-dependent high statistics measurement of b-quark production becomes available, an independent determination of $|V_{ub}|$ and $|V_{cb}|$ CKM matrix elements will be possible as well [1].

Of course, heavy quark production is not the only way of studying the nucleon structure. Quark densities are usually measured in DIS-type experiments. These measurements are naturally performed in neutrino-nucleon interactions. Here, νFMSR offers a tantalizing possibility to measure parity-violating *polarized* nucleon structure functions. These measurements were considered hopeless in νN experiments due to the enormous technical difficulties in polarizing heavy targets, the only possible targets for neutrino accelerator experiments if sufficient statistics is expected. At νFMSR, light targets (like H_2 or D_2), which are relatively easy polarized, can be used due to the large density of neutrino beam. A number of unique measurements (such as the measurement of parity-violating polarized structure function of neutron) is possible [1].

C   Charmonium production and gluon density

High intensity neutrino beams would also allow studies of *charmonium* production, a sensitive probe of the gluon distribution function in the nucleon. Contrary to the open-flavor meson production, the production of charmonium states can be described in a model-independent fashion using the factorization theorems of Non-Relativistic QCD (NRQCD),

$$\sigma(A + B \to H_{c\bar{c}} + X) = \sum_n \frac{F_n}{m_c^{d_n-4}} \langle 0|\mathcal{O}_n^H|0\rangle, \tag{7}$$

which separates short-distance physics, represented by the coefficients F_n (which might be sensitive to various parton distribution functions) from the long-distance physics, represented by the NRQCD matrix elements

$$\langle 0|\mathcal{O}_n^H|0\rangle = \sum_X \sum_{m_J} \langle 0|\mathcal{K}_n|H_{m_J} + X\rangle \langle H_{m_J} + X|\mathcal{K}_n'|0\rangle, \tag{8}$$

and determine the probabilities of charm quarks produced in the various angular momentum and color (singlet and octet) states by action of NRQCD operators $\mathcal{K}_n^{(l)}$ to evolve into a physical charmonium state, like a J/ψ. At the moment, these matrix elements cannot be computed model-independently. However, they are *universal* (i.e. process-independent), so they can be extracted from other experiments. Clearly, J/ψ produced in sufficiently high numbers can be used to study gluon distribution function in the wide range of x [7].

A major advantage of using the neutrino beam is that, at leading order in α_s, the spin structure of the νZ coupling selects a certain combination of octet operators. The largest contribution is from the one with the quantum numbers ${}^3S_1^{(8)}$. The differential cross section was calculated in [7]:

$$\frac{d\sigma\left(s, Q^2\right)}{dQ^2} = \frac{\pi^2 \alpha^2 \alpha_s}{3 \sin^4 2\theta_W} \frac{1}{\left(Q^2 + m_Z{}^2\right)^2}$$
$$\times \sum_n \frac{\langle 0|\mathcal{O}_n|0\rangle}{m_c^3} \int_{\frac{Q^2+4m_c^2}{s}}^{1} dx\, f_{g/N}\left(x, Q^2\right) h_n\left(y, Q^2\right), \tag{9}$$

where s is the total invariant mass of the νN system, x is the momentum fraction of the incoming gluon, $-Q^2$ is the momentum-squared transferred from the leptonic system, $y = \frac{Q^2+4m^2}{sx}$, and $f_{g/N}(x, Q^2)$ is a gluon distribution function in the nucleon. The charmonium structure functions are given by

$$h_{{}^1S_0^{(8)}}\left(y, Q^2\right) = (g_V^c)^2 \times 6\frac{Q^2 m_c^2}{\left(Q^2 + 4m_c^2\right)^2}\left(y^2 - 2y + 2\right)$$

$$h_{{}^3S_1^{(8)}}\left(y, Q^2\right) = (g_A^c)^2 \times 2m_c^2 \frac{Q^2(y^2 - 2y + 2) + 16(1 - y)m_c^2}{\left(Q^2 + 4m_c^2\right)^2}$$

$$h_{{}^3P_0^{(8)}}\left(y, Q^2\right) = (g_V^c)^2 \times 2\,Q^2 \frac{\left(Q^2 + 12m_c^2\right)^2}{\left(Q^2 + 4m_c^2\right)^4}\left(y^2 - 2y + 2\right) \tag{10}$$

$$h_{{}^3P_1^{(8)}}\left(y, Q^2\right) = (g_V^c)^2 \times 4\,Q^4 \frac{Q^2(y^2 - 2y + 2) + 16(1 - y)m_c^2}{\left(Q^2 + 4m_c^2\right)^4}$$

$$h_{{}^3P_2^{(8)}}\left(y, Q^2\right) = (g_V^c)^2 \times \frac{4}{5}\,Q^2 \left[\frac{(y^2 - 2y + 2)Q^4}{\left(Q^2 + 4m_c^2\right)^2}\right.$$
$$\left. + \frac{48(1 - y)Q^2 m_c^2 + 96(y^2 - 2y + 2)m_c{}^4}{\left(Q^2 + 4m_c^2\right)^2}\right],$$

where $g_A^c = \frac{1}{2}$ and $g_V^c = \frac{1}{2}\left(1 - \frac{8}{3}\sin^2\Theta_W\right)$ are the vector and axial couplings of the c-quark. Clearly, the coupling constants favor the ${}^3S_1^{(8)}$ contribution, which is due to the large axial coupling (a similar contribution is, of course, absent in the case of J/ψ lepto- and photoproduction). Indeed a numerical estimate [7] shows that this matrix element dominates the total cross section, and also the differential

TABLE 1. Total cross sections for the J/ψ production in $\nu N \to J/\psi X$ for various incident neutrino energies.

$E_\nu[GeV]$	7.5	25	120	450
$\sigma[nb]$	7.8×10^{-13}	6.9×10^{-10}	1.3×10^{-8}	5.5×10^{-8}

cross section unless $Q^2 \gg m_c^2$. At large Q^2, the relative Q^4 enhancement of the P-wave structure functions makes them dominant. These structure functions should be incorporated in the specific Monte Carlo generators built for the particular detector design.

An important question to address is the expected event rate of J/ψ production. Computing the total cross sections for the J/ψ production (Table (1)), a simple calculation shows that currently running neutrino experiments NOMAD and NuTeV could collect a few J/ψ events (due to either low energy of the neutrino beam or particular detector configuration) and "confirm" the color octet mechanism. On the contrary, a neutrino experiment at the future Muon Collider would collect about 3×10^3 events/year and provide precise measurement of various NRQCD matrix elements and/or the gluon distribution function.

D   Neutrino factory = charm factory?

It is clear from the preceding discussion that charm production plays an important role in the studies of nucleon structure and electroweak parameters. It is also important that with the estimated 10^8 well-reconstructed charm events [1] νFMSR is also an impressive *charm factory*. Charm physics is an important complement to the B-physics program at B-factories (see, e.g. [9]). Besides testing our understanding of QCD effects in charmed particle decays, it also offers an opportunity to look for the effects of new physics in rare decays of charmed mesons, CP-violating asymmetries and $D\bar{D}$ mixing studies, as the standard model background to this processes is tiny [10].

It is interesting to see if νFMSR has any advantages over the existing charm experiments. One important advantage of $D\bar{D}$ mixing analysis performed at νFMSR that is not available elsewhere involves initial D flavor tagging. In particular, D^0 mesons produced in *charged* current interactions receive an automatic initial flavor tag in the form of the final state lepton charge. Correlation studies of the charges of the "tag" lepton and, say, lepton from the semileptonic charm decay would offer experimentally clean signatures of $D\bar{D}$ mixing.

III   RARE PROCESSES

Neutrino-nucleon processes at low momentum transfer are sensitive to generic four-fermion contact terms produced by the high energy neutral current interactions. These four-fermion interactions can be associated with supersymmetric

theories with $\mathcal{R}$-parity nonconservation, new vector bosons, quark compositness or even loop effects associated with the new flavor-changing neutral current interactions [1]. Consider, for instance, the low energy remnant of a generic high energy electron-quark neutral current interaction. It can be represented by

$$\mathcal{L}_{NC} = \sum_q \Big[\eta_{LL}^{eq} \left(\overline{e_L} \gamma_\mu e_L \right) \left(\overline{q_L} \gamma^\mu q_L \right) + \eta_{RR}^{eq} \left(\overline{e_R} \gamma_\mu e_R \right) \left(\overline{q_R} \gamma^\mu q_R \right)$$
$$+ \eta_{LR}^{eq} \left(\overline{e_L} \gamma_\mu e_L \right) \left(\overline{q_R} \gamma^\mu q_R \right) + \eta_{RL}^{eq} \left(\overline{e_R} \gamma_\mu e_R \right) \left(\overline{q_L} \gamma^\mu q_L \right) \Big] . \tag{11}$$

A similar equation can be written for a direct neutrino-quark interactions. One can use $SU(2)$ symmetry to relate ν and e couplings

$$\eta_{LL}^{\nu u} = \eta_{LL}^{ed} , \;\; \eta_{LL}^{\nu d} = \eta_{LL}^{eu} ,$$
$$\eta_{LR}^{\nu u} = \eta_{LR}^{eu} , \;\; \eta_{LR}^{\nu d} = \eta_{LR}^{ed} ,$$

so that νN interactions can be used to constrain η's of the Lagrangian of Eq. (11). A particular example of a high-energy model that leads to the low-energy Lagrangian of this type is provided by $\mathcal{R}$-parity violating SUSY, where at low values of transferred momenta one can integrate out heavy $\tilde{e}_L{}_R^i$ and $\tilde{d}_L{}_R^i$ to rewrite the Lagrangian in terms of local four-fermion interactions. Assuming that the squarks of first two generations are degenerate and imposing $SU(2)$ symmetry constraints,

$$\eta_{LR}^{ed} = -\frac{(\lambda'_{1j1})^2}{2m_{\tilde{u}_L^j}^2} = -\frac{(\lambda'_{1j1})^2}{2m_{\tilde{d}_L^j}^2} = \eta_{LR}^{\nu d}. \tag{12}$$

Here λ'_{ijk} is a parameter of the original $\mathcal{R}$ SUSY Lagrangian. Indeed, the best constraint on this coupling, $\eta_{LR}^{ed} < 0.07^{+0.24}_{-0.24}$ comes from the analysis of neutrino nucleon scattering experiments [11]. Other new physics scenarios involve new heavy neutral leptons (models with $H_L^0 - \nu_\mu$ mixing) [12] or new neutral gauge bosons like Z' which appears in many superstring-motivated models.

IV CONCLUSIONS

New experiments utilizing high energy and intensity neutrino beams would offer a unique opportunity to perform new precision studies of QCD and electroweak interactions. New types of measurements, like charmonium production and extractions of V_{cb} and V_{ub} CKM matrix elements, will become possible. Interesting new physics scenarios can also be explored. As a result, a high intensity neutrino facility could prove to be a very useful addition to the Muon Collider physics program.

REFERENCES

1. I.I. Bigi *et. al.* "An overview of the potential for neutrino physics at future muon collider complexes". Work in progress.

2. C.H. Llewellyn Smith, Nucl. Phys. **B228**, 205 (1983).

3. E.A. Pascos and L. Wolfenstein, Phys. Rev. **D7**, 91 (1973).

4. H. Georgi and H.D. Politzer, Phys. Rev. **D14**, 1829 (1976).

5. J.M. Conrad, M.H. Shaevitz and T. Bolton, Rev. Mod. Phys. **70**, 1341 (1998).

6. M.A. Aivazis, J.C. Collins, F.I. Olness and W. Tung, Phys. Rev. **D50**, 3102 (1994).

7. A.A. Petrov and T. Torma, Phys. Rev. **D60**, 093009 (1999).

8. P. Cho and A.K. Leibovich, Phys. Rev. **D53**, 150 (1996).

9. P.F. Harrison and H.R. Quinn, eds. [BaBar Collaboration] *The BaBar physics book*, SLAC Report SLAC-R-504, 1998.

10. For the most recent analysis see, e.g. E. Golowich and A. A. Petrov, Phys. Lett. **B427**, 172 (1998); A. A. Petrov, Phys. Rev. **D56**, 1685 (1997); G. Burdman, E. Golowich, J. L. Hewett and S. Pakvasa, Phys. Rev. **D52**, 6383 (1995); G. Burdman, hep-ph/9508349, and references therein.

11. D. Zeppenfeld and K. Cheung, hep-ph/9810277.

12. M. Gronau, C.N. Leung and J.L. Rosner, Phys. Rev. **D29**, 2539 (1984).